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NASA Technology Investments in Electric Propulsion: New Directions in the New Millennium

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NASA TECHNOLOGY INVESTMENTS IN ELECTRIC PROPULSION: NEW DIRECTIONS IN THE NEW MILLENNIUM

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SUMMARY

The last decade was a period of unprecedented acceptance of NASA developed electric propulsion by the user community. The benefits of high performance electric propulsion systems are now widely recognized, and new technologies have been accepted across the community. NASA clearly recognizes the need for new, high performance, electric propulsion technologies for future solar system missions and is sponsoring aggressive efforts in this area. These efforts are mainly conducted under the Office of Aerospace Technology. Plans over the next six years include the development of next generation ion thrusters for end of decade missions. Additional efforts are planned for the development of very high power thrusters, including magnetoplasmadynamic, pulsed inductive, and VASIMR, and clusters of Hall thrusters. In addition to the in-house technology efforts, NASA continues to work closely with both supplier and user communities to maximize the acceptance of new technology in a timely and cost-effective manner. This paper provides an overview of NASA's activities in the area of electric propulsion with an emphasis on future program directions.

INTRODUCTION

The last decade was a period of unprecedented acceptance of NASA developed electric propulsion by the user community. The benefits of high performance electric propulsion systems are now widely recognized and new technologies have been accepted across the community. The beginning of the decade saw two generations of hydrazine arcjets become operational for North-South Stationkeeping on Lockheed-Martin commercial communications satellites. After 40 years, NASA ion propulsion has entered the mainstream. Deep Space-1 with the NSTAR ion system is the first flight of a xenon ion system as primary propulsion on a deep space NASA mission. On the commercial side, Hughes has flown their XIPS-13 on the 601 HP bus and the XIPS-25 is operational on the 702 bus. Hall thrusters are routinely used on Russian communication satellites for both East-West and North-South Stationkeeping. NASA has been heavily involved in transitioning the Russian developed Hall thruster technology for use on U.S. spacecraft. The October 1998 flight of the RHETT2/EPDM Thruster with Anode Layer on the NRO STEx spacecraft was the first Western flight of a Hall thruster. NASA has supported the efforts of all U.S. providers and users of Hall thruster systems by providing test facilities and expertise at both its Glenn Research Center (GRC) and Jet Propulsion Laboratory (JPL). In the area of control propulsion NASA GRC and the Goddard Space Flight Center (GSFC) have developed a pulsed plasma thruster which is awaiting launch on the Earth Observing-1 spacecraft. The system will serve as a precursor for future NASA missions, requiring propulsive attitude control.

In-Space propulsion system mass fractions continue to drive mission performance across a wide range of Earth-orbital and deep space missions. Increasing the performance of those systems is a key element in allowing NASA to lower the cost of space transportation, which will enable planned science missions and provide technology spin-offs to the commercial space sector. NASA’s electric propulsion effort is centered on providing products to its three mission enterprises of Earth Science, Human Exploration and Development of Space, and Space Science. The major support for the technology is NASA’s Aerospace Technology Enterprise under both the new Space-Base program, which was formed from the former Cross Enterprise Technology Development Program (CETDP), and the Advanced Space Transportation Program managed by the Marshall Space Flight Center (MSFC). Technical participation is provided from several centers including, GRC, GSFC, JPL, Johnson Space Center (JSC), and MSFC. To advance the technology into higher technology readiness levels and to eventual mission acceptance, the technology programs seek partners from the mission enterprises. A major future technology customer is the Space Science Enterprise, which is currently providing support under the Deep Space Exploration Technology Program to support NSTAR-class ion propulsion evolution. Over the last year a significant amount of planning and content development of the electric propulsion portion of the Advanced Space Transportation Program was completed with identification of key products and technology milestones to meet/exceed Access to Space goals. The plans encompass the next six years and will move NASA’s electric propulsion effort in new directions. Building on the last decade’s successes, NASA's emphasis in the next decade will focus on technology development to enable missions planned at the end of the decade and beyond. The first major emphasis will include development of the next generation of electrostatic systems for planetary and near Earth operations with power levels of 10's of kilowatts. The second exciting area of emphasis is centered on very high power electric propulsion. After a decade of very limited investment, NASA is again planning on conducting research and development of 100 kW ≥ 1MW electric propulsion concepts for solar system exploration.

ION THRUSTER

The largest technology investment for NASA in electric propulsion continues to be the area of ion propulsion for deep space missions and is being developed by NASA GRC and JPL. Ion propulsion technology for primary spacecraft propulsion was successfully demonstrated for the first time on the Deep Space-1 (DS1) mission following its launch in October 1998. The ion propulsion system (IPS) on DS1 included a single ion engine and its associated support hardware. The DS1 ion engine has now accumulated more operating time in space than any rocket engine in the history of the space program. As of Sept. 25, 2000 the thruster on DS1 had accumulated 5830 hr of operation. The DS1 ion propulsion system is currently being used for both primary propulsion and for pitch and yaw attitude control of the spacecraft. Even when IPS thrusting is not required for the trajectory, the ion thruster is kept on to provide spacecraft pitch and yaw control in order to save hydrazine propellant for the September 2001 encounter with the comet Borrelly. As a result, the ion thruster is being operated for between 165 and 167 hr/week, and will accumulate a total of ~14 000 hr of operation by the end of the mission.

A long-duration test with the DS1 flight spare ion engine is ongoing at JPL and has demonstrated over 12 900 hr of operation to date. Over this time the engine has processed 113 kg of xenon, representing 130 percent of the engine design life. This test is scheduled to demonstrate a 125-kg xenon propellant throughput capability (150 percent of the design life) by the end of the year 2000. If the engine continues to run well, this test will be extended in order to demonstrate a propellant throughput capability >125 kg.

Advanced ion propulsion technology is considered mission enabling or strongly mission enhancing for a wide variety of deep space missions including Comet Nucleus Sample Return (CNSR), Titan Explorer, Venus Sample Return, Neptune Orbiter, Saturn Ring Observer, and Europa Lander. Future missions will require multiengine ion propulsion systems. An advanced, multiengine version of the DS1 ion propulsion technology is needed to take full advantage of the performance benefits of ion propulsion. Future missions need an ion engine with a total impulse capability of approximately twice the NSTAR/DS1 design point in order to reduce the number of required ion engines.

The objective of NASA's near-term ion propulsion system technology activity is to develop an advanced multiengine, ion-propulsion-system in order to retire the risk for future deep-space missions requiring the use of advanced solar electric propulsion (SEP) systems. The IPS technology developed under this task will enable significantly more difficult deep-space missions by increasing the total impulse, specific impulse and maximum thrust capability of the ion engine. In addition, the multiengine SEP system developed will provide a single fault tolerant capability that is highly desirable for flag-ship deep-space science missions.

n addition to the DS-1/NSTAR activities, NASA's ion technology efforts are focused on base technology research including long-life optics, neutralizers, discharge chambers, and diagnostics and four main areas of thruster system development: 10 kW class, 300 W class, microion, and 30 kW-class/14 000 sec Isp engine technology.

10 k engine

The goal of this effort is to develop a high-performance 10 kW ion engine which is throttleable down to 2.5 kW, along with the associated power processing technology. The target customer for the technology is the ambitious class of NASA deep-space exploration missions beyond 2007. With deep throttle capability and an Isp range of 2500 to 5000 sec, the goal is to develop an engine with application both to commercial Earth Space operations and for NASA deep space science.

To accomplish that overall objective several goals have been established. These include:

- 2.5 to 10 kW power-throttling envelope
- Variable specific-impulse capability of ~2500 to 5000 sec specific impulse for Earth-space mission applications, and 4000 sec and 70 percent efficiency for deep-space applications
- at least 1500 hr lifetime at low specific impulse, and 8000 hr lifetime at high specific impulse

- mechanical design envelope comparable to that of the NASA NSTAR 30 cm thruster
- mass less than SOA commercial 25 cm thruster technology
- PPU specific mass less than that of NSTAR PPU
- PPU efficiency >92 percent

This development activity is being pursued aggressively in FY01. The first year's activity will be performed in-house at GRC and will include thruster design and performance analysis, completion of detailed mechanical design of thruster components, fabrication of thruster components, and assembly of prototype thruster. At the end of a year of development preliminary thruster performance testing will be conducted. University participation will include the University of Michigan for both ion optics erosion modeling and engine erosion diagnostics development.

Proposals for conducting a design study of innovative approaches to simplified ion power processing unit (PPU) designs were solicited, with Hughes Electron Dynamics selected as the contractor. The purpose of this procurement is to advance the systems technology of electrostatic (ion) propulsion power processing, beyond the state-of-the-art NSTAR technology.

The desired result is an ion PPU design that can be expected to operate at high power (~5 kW) and high efficiency (>92 percent), while yielding a low mass (less than the 15 kg flight-packaged PPU, less cabling). Approaches which reduce the manufacturing costs via reduction in parts count and incorporation of simplified power processing schemes, while maintaining low mass and volume are expected.

The product of the on-going first-year design study includes top-level drawings of the breadboard PPU, detailed design schematics for the breadboard beam supply, and a breadboard beam supply. A follow-on option to manufacture a complete breadboard PPU and engineering-model hardware is anticipated in FY02.

Subkilowatt

At GRC a breadboard power processor was fabricated and successfully integrated with a next generation laboratory model 8 cm thruster. Most recently, a second-generation lightweight breadboard power processor, constructed using multi-function power supplies and printed circuit board layout has been manufactured. Four power converters are used to produce the required six electrical outputs. Due to similar output current requirements, the discharge supply is also used for cathode heating by using relays to switch the output. The switching frequency was also increased from that used in the first breadboard, to reduce the size of the magnetic components. The component mass of this breadboard is 0.9 kg and the total mass is 1.8 kg.

Industry proposals for conducting a design study of innovative approaches to simplified low-power (subkilowatt) ion thruster and power processors were solicited. Two contractors were selected, Hughes Electron Dynamics and Primex Aerospace Company. The product of the design study is to include a user survey (identifying potential mission applications), top-level drawings, and detailed system and performance requirements. A follow-on option to manufacture engineering-model thrusters and power processors is anticipated.

Microion

It is the goal of this activity to establish the feasibility of developing a "micro" ion thruster, based upon low-power hollow cathode technology. Overall performance objectives for this Hollow Cathode Micro Thruster (HCMT) are an efficiency exceeding 25 percent at >1500 sec specific impulse, operating over an input power range of about 1 to 25 W.

A general need for high specific impulse (>1000 sec), low-power (~10 W) propulsion has been identified for 2nd generation NASA Microspacecraft. This thruster fills the gap between microNewton concepts and ~100W class electric propulsion thrusters, and has the potential to be used on a variety of microspacecraft for prime propulsion, stationkeeping, and formation flying.

The HCMT is a novel approach to low power electric propulsion that promises high specific impulse, good efficiency, and high reliability in a small, easily-fabricated package. The HCMT will provide thrust by accelerating ions produced by a miniature hollow cathode utilizing a high-voltage acceleration stage. The thruster overcomes the technological roadblocks that prevent scaling down conventional ion engines and Hall-Effect Thrusters (HETs) because the ionization process eliminates the issues of neutral loss and magnetic confinement. Recent advances enabling this concept include the development at NASA GRC of small hollow cathodes which are capable of supporting high ionization efficiencies, and the quantitative understanding developed via computer models of hollow cathode ion production. These models show that in certain regimes, small hollow cathodes can ionize a high fraction of propellant at relatively low power levels. Using the ions from the hollow cathode directly eliminates the need for a separate ionization chamber and associated power supply and magnets as compared with typical means of ion production.

To address this need, laboratory investigations have been undertaken at NASA GRC to examine the basic physics controlling ionization processes of low power 3.2 mm diameter cathodes, and a contracted effort at Maxwell Laboratories is underway to develop computer models of this process. This has resulted in fabrication of high-efficiency hollow cathodes (>50 percent ionization efficiency), and identification of the controlling design parameters. Fabrication of the first prototype HCMT has been completed and performance testing will be performed over the next year.

Interstellar Precursor Ion

This activity is long-range and seeks to develop 10 to 30 kW krypton ion engine technology in support of high specific impulse (>10 000 sec) applications such as the Interstellar Probe Mission. The activity is being conducted in-house by GRC and includes university participation from Colorado State University in the area of ion optics design analysis and the Ohio Aerospace Institute for engine test support.

The first-phase of the effort was completed in FY00 and resulted in the completion of the design and fabrication of a 76 cm diameter discharge chamber. The discharge chamber was integrated with an ion extraction system and neutralizer. Discharge operation was subsequently characterized on krypton and xenon propellants, and engine performance was characterized on xenon propellant up to ~4 kW input power.

While development of large-area, large-gap, high-voltage (>10 kV) optics was beyond the scope of this initial phase, there was interest in obtaining data on discharge operation with beam extraction. To circumvent the difficulties previously encountered with large space-to-gap 50 cm diameter ion optics, a novel approach to large-area beam extraction was used on this engine. The approach was to use multiple ion optics sets of a proven design and of smaller diameter and span-to-gap, to extract the ion current from a common discharge chamber.

There are several potential advantages to this design approach to ion extraction systems, which may hasten the development of very high-power ion engines. These include: elimination of the fabrication and assembly issues (mechanical tolerances, etc.) associated with large-area, large span-to-gap ion optics; indefinite engine size scaling capability; and expanded engine throttling range.

In this case, three 30 cm diameter (nominal 28.2 cm beam diameter) NSTAR-type ion optics sets were affixed to the forward end of the discharge chamber. The combined optics area is 1874 cm^2, which is approximately that of a single optics set of 50 cm beam diameter, yet it only has a span-to-gap ratio of about 430. Perveance data obtained from this ion optics system indicates that each of the 3 ion optics sets is functioning on the 76 cm diameter discharge chamber in the same manner as they would individually mounted to 30 cm diameter discharge chambers.

This is an important finding, demonstrating that the use of multiple ion extraction systems on a common discharge chamber will function stably; and yield an increase in beam current extraction capability proportional to the increase in total beam area. This is especially significant for engine scaling, given prior experience with 50 cm diameter ion optics which were incapable of extracting beam currents comparable even to those of 30 cm diameter ion optics.

The second-phase effort beginning in FY01 will concentrate on development of the high-voltage ion optics, to include operation of the engine on krypton propellant at high (>10,000 sec) specific impulse. FY01 Activities will include design analyses and fabrication of large-area high-voltage ion optics, completion of design modifications to discharge chamber to accommodate high-voltage beam extraction operation, completion of facility upgrades in GRC electric propulsion test-beds to install a power console for engine operation up to 30 kW @ 15-kV), and to develop control sequence for high-voltage arc breakdowns. Finally, engine performance tests with beam extraction on krypton propellant will be initiated.

Space-Base Ion Technology

<u>5 kW 30 cm Testbed Engine</u>.—A significant level of activity is being expended on ion component technology development with broad application to the focused efforts for missions before 2007. To enable the technology development, a 30 cm test-bed engine has been fabricated by NASA GRC to have operating capability up to 5 kW. The engine is identical in design to the NSTAR flight thruster (with the exception of chamber material) to provide a test-bed for the development of components (ion optics, discharge and neutralizer cathodes, propellant isolators, etc.). The test-bed allows for detailed investigations of performance and erosion processes relative to the NSTAR thruster, for which a large database has been established. It also accommodates experimental activities focused to

improve the NSTAR thruster performance, as well as to conduct component technology development for a potential comet sample return mission, which has baselined a 30 cm NSTAR-derivative engine.

High-Performance, Long Life Ion Optics

Several options, including advanced-molybdenum, titanium, and carbon-carbon materials, with potential for 2x to 10x increase in propellant throughput capacity over that demonstrated with NSTAR 30 cm ion optics, are being pursued at GRC, and under grant and contract. These options, through materials selection, design, or both, should yield a reduction in sputter erosion due to ion bombardment, and hence increase in grid life.

To date, 30 cm diameter molybdenum ion optics with 50 percent increase in accelerator grid thickness (over NSTAR optics), and multiple sets of 30 cm diameter optics made from titanium (with a geometry comparable to that of NSTAR ion optics), have been successfully fabricated in-house and tested up to 4.6 kW input power on a test-bed thruster. Performance (perveance, and electron backstreaming margin) for the titanium ion optics compare favorably to that measured for NSTAR ion optics. Both designs appear to be leading candidates for applications requiring up to ~170 kg propellant throughput, up to at least 3 kW.

Under grant to Colorado State University, the use of ion-implantation processes to reduce the sputter yield of molybdenum is being investigated. To date a 15 percent reduction in sputter yield via implantation of nitrogen, and a 40 percent reduction in sputter yield via implantation of carbon, has been demonstrated on sample materials. This is a potentially attractive approach to increasing grid life, which would not require alteration of the base material or electrode configuration. Additional investigations are intended to evaluate the manufacturing viability of this approach with large-area ion optics, and to examine the reduction in sputter yields feasible with titanium base material.

The development of ion optics manufactured from carbon-carbon is being pursued under contract with Ceramic Composites, Inc. Carbon-carbon provides the highest-payoff in the near term for grid life enhancement, and is a leading candidate for high-thrust density 5 to 10 kW engines. In the first phase of the contract, multiple sets of ion optics (electrodes and mounting system) will be delivered, compatible with the design of the NASA subkilowatt (8 cm beam diameter) ion thruster. After performance evaluations, phase two of the contract will involve fabrication and delivery of multiple sets of ion optics compatible with NASA's 30 cm thruster. To date, detailed designs of the 8 cm ion optics have been completed by the contractor, and fabrication of manufacturing tooling has been completed.

High-Efficiency, Long-Life Neutralizers

For both improved-efficiency NSTAR-class ion thrusters operating at sub-2.3 kW power levels, as well as 5 kW-class thrusters, improvements in neutralizer performance (reduction in propellant and power consumption) are warranted. An effort has been initiated to develop an improved-performance neutralizer specifically for the NSTAR 30 cm thruster.

A series of design-optimization tests were conducted on prototype cathodes, examining the affect of cathode and keeper orifice plate geometries on neutralizer function. Significant benefit was gained due to a parallel development activity being conducted for a reduced flow rate cathode for the Space Station plasma contactor system. This thruster activity culminated in the manufacturing of two identical engineering model neutralizer assemblies, both of which have been successfully integrated on NASA 30 cm thrusters, and performance characterized up to about 3.1 kW thruster input power. Use of the improved neutralizer increases thruster efficiency by about 3 and 5 percentage points at 2.3 and 0.5 kW respectively.

Additional work will be required to further improve performance, and to validate the lifetime, for a low-flow neutralizer product. For operation up to 5 kW, beam currents of up to about 2.7 A will be required, necessitating the development of a new, higher-current neutralizer cathode with larger dynamic current range, and low power and propellant consumption.

Improved Discharge Chamber Design

An effort was initiated to investigate the thermal-limits of NSTAR-derivative 30 cm thrusters, and to examine discharge processes with the intent of developing an improved-performance thruster capable of 5 kW operation. To examine temperature limits, the test-bed thruster was outfitted with 34 Type K thermocouples distributed over the discharge chamber, discharge and neutralizer keepers, high-voltage propellant isolators, thruster mounting system, and plasma screen to document the thruster thermal behavior. While the thruster components thought to be most critical were the rare-earth magnets and high-voltage propellant isolators, temperature data from the rest of the thruster was needed to assess heat transfer characteristics. Temperature measurements at all magnet rings in the discharge chamber were documented up to 4.5 kW thruster input power, and the maximum recorded magnet temperature was ~330 °C, which is within the limits defined by the manufacturer.

Internal plasma measurements at the anode of the test-bed thruster were measured and used to estimate the upper limit of electron flux collected between the magnetic cusps. This upper limit suggests that about 30 percent of the discharge current flows to anode surfaces between the cusps. It was also found that the majority of both ion and electron collection between cusps occurred in the downstream cylindrical section of the discharge chamber. This finding suggests that the discharge may be localized in the cylindrical section of the thruster.

Additionally, it was found that the electron temperature was on average 3 eV higher in the cylindrical section as compared with the upstream conic section of the discharge near the hollow cathode. This finding suggests that the thermalization rate of primary electrons in the cylindrical section may be higher than in the conical section of the thruster. The thermalization of primaries in the cylindrical section may be enhanced due to electron confinement associated with the negatively-biased screen grid electrode.

Discharge and Beam Diagnostics

The research at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan has focused on measuring discharge cathode erosion using laser-induced fluorescence (LIF), and explaining the physical mechanism behind this erosion. The LIF diagnostic, using a ring-dye laser, has demonstrated three-component ion (Xe+) velocimetry and has successfully interrogated Xe, Xe+, Mo and W species.

The investigation of the generation of ions capable of causing the erosion observed in the NSTAR 2000 hr wear test has made significant progress. A NASA GRC 30 cm ion thruster, modified to provide optical access to the discharge chamber was used for these tests, and assessments were made over the entire 2.3 kW NSTAR throttling range. Internal LIF of the thruster discharge indicates the presence of a small potential hill and back-flowing ions near the unkeepered discharge cathode. Ion energies, especially of Xe++ and Xe+ coupled with a potential drop across the sheath around the cathode appear sufficient to generate the observed erosion.

A deconvolution capability was developed which permits calculation of Xe+ velocities. Detailed Xe+ velocity mapping indicates significant radial and, at the upstream edge, noticeable back-flowing velocities which are consistent with the erosion patterns observed in the 2000 hr wear test. Tungsten LIF signals as a function of radial position across the face of the unkeepered cathode have also been obtained, and agree with the observed erosion. Both sets of data were taken with the thruster operating at 2.3 kW input power and 12.1 A discharge current. A detailed correlation between Mo and W LIF signal, Xe+ velocities, thruster operating condition, and cathode erosion rates has been developed.

To reduce the risks associated with new ion propulsion systems, ground based lifetests will continue to be conducted for the foreseeable future. Validating new thrusters for increased propellant throughput is a costly prospect, with the cost of qualifying thrusters for space-flight measured in millions of dollars. Life-limiting operating conditions must be identified and mitigated prior to initiating long duration tests to increase the probability of success. Consequently, accurate and timely evaluations of thruster performance and predicted life are critical to the development of advanced ion thruster systems.

Research is currently being conducted at NASA GRC, with the assistance of the Ohio Aerospace Institute, to develop real-time, spatially-resolved erosion diagnostics in support of advanced ion thrusters. As a preliminary step toward developing real-time erosion diagnostics, emission spectra have been collected in the discharge chamber and the beam of the test-bed 30 cm thruster.

Detailed plume measurements of the test-bed thruster have also been documented, using both Faraday and Langmuir probes. It was found that the beam profile becomes more peaked with increasing thruster power. Beam divergence measurements revealed that the beam divergence angle was fairly narrow, with 90 percent of the beam included within 25° (for conventional NSTAR ion optics). It was also found that the radial electric field component in the plume is not capable of imparting significant off-axis energy to those ions born on centerline, to sputter typical spacecraft materials. Plasma measurements in the plume were also used to estimate relative contributions to low energy ion production in the plume due to charge-exchange and direct ionization.

PULSED INDUCTIVE THRUSTER

Unlike other high power electric propulsion systems, the PIT is an electrodeless device in which the plasma does not directly contact material surfaces, thus minimizing erosion and increasing thruster life. The specific impulse can be tailored to meet mission requirements, allowing optimized trip times and reducing propellant mass. In addition, a single thruster design can be used for a variety of mission applications, ranging from orbit transfer to deep space exploration as additional on-board power becomes available. In its basic form, the PIT consists of a flat spiral coil covered by a thin dielectric plate. A pulsed gas injection nozzle distributes a thin layer of gas propellant across the plate surface at the same time that a pulsed high current discharge is sent through the coil. The rising current creates a time varying magnetic field, which in turn induces a strong azimuthal electric field above the coil. The electric field ionizes the gas propellant and generates an azimuthal current flow in the resulting plasma. The current in the plasma and the current in the coil flow in opposite directions, providing a mutual repulsion that rapidly blows the ionized propellant away from the plate to provide thrust. The thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow, and there is minimal if any erosion due to the electrodeless nature of the discharge.

State of the art performance measurements for the PIT were obtained by TRW under single-shot discharge conditions. Using ammonia propellant and a 16-kV capacitor bank charging voltage, 1-m diameter thruster efficiencies of 35 to 55 percent were achieved for specific impulse values of 2000 to 8000 sec, respectively. The planned technology development program includes GRC, MSFC, TRW, and OAI participation, and the ultimate goal of the proposed technology program is to demonstrate efficient pulsed inductive thruster performance under high frequency, multiple repetition rate operation. The specific goal is to demonstrate a thruster efficiency of at least 60 percent for repetitively pulsed discharges of 10 to 100 pulses discharged at 10 Hz or higher with peak power levels exceeding 1-MW.

Initial work will focus on thruster physics simulation. A simple equivalent circuit model of the PIT acceleration mechanism has been developed by TRW, but to date no significant attempt has been made to develop a physics-based numerical model to understand and improve thruster performance. A time-dependent MHD simulation will be developed to model the plasma ionization and acceleration mechanisms and identify techniques to improve thruster performance. TRW will design a repetitively-pulsed propellant injection system, an active coil cooling system, and high energy, multiple rep-rate power storage and delivery system for a multiple repetition rate version of the MW-class pulsed inductive thruster. After the design is complete, they will fabricate and test thruster and control circuit components and assemble the multiple rep-rate PIT. Previous single-shot data for the PIT was collected in a small TRW vacuum chamber. These single-shot measurements will be repeated with the new PIT design in GRC's large chambers to validate prior performance measurements and establish operating guidelines for multiple-repetition rate operation. The insight provided by the numerical simulations and the performance measurements obtained during multiple-rep rate (burst-mode) operation will provide sufficient information to design and develop a continuously pulsed prototype of the PIT for extended ground testing in a simulated space environment. Augmented funding will provide for the fabrication of a continuously pulsed prototype thruster, and for extended duration ground tests under realistic in-space operating conditions. These long-duration thruster ground tests will provide critical information on repetitively pulsed thruster performance and life issues.

MAGNETOPLASMADYNAMIC

The high power magnetoplasmadynamic (MPD) thruster is a robust and versatile electromagnetic propulsion device with the potential to meet a variety of high-power, near-Earth and deep space mission requirements. In its basic form, the MPD thruster consists of a central cathode surrounded by a concentric cylindrical anode. A high-current arc is struck between the anode and cathode, which ionizes and accelerates a gas propellant. In the self-field version of the MPD thruster, an azimuthal magnetic field produced by the return current flowing through the cathode interacts with the radial discharge current flowing through the plasma to produce an axial body force. In applied-field versions of the thruster, a solenoid magnet surrounding the anode is used to provide additional radial and axial magnetic fields that can help stabilize and accelerate the discharge plasma.

The specific impulse (Isp) of the thruster is a function of the discharge current and propellant species. Low molecular weight propellants such as hydrogen and lithium can provide Isp values in excess of 5,000 sec, while heavier propellants such as argon and krypton are generally limited to below 2 500 sec. Although thruster efficiencies as high as 70 percent were reported in the early 1970's using lithium propellant, more recent performance measurements have demonstrated lower efficiencies of around 45 percent with lithium and 15 to 30 percent for most other propellants. In addition, the stability of the MPD thruster plasma discharge is limited by the onset of voltage oscillations that can lead to enhanced electrode erosion and a rapid reduction in thruster life. Nevertheless, the MPD thruster is unique in its ability to process megawatts of power, and the technology continues to hold significant promise as a high power plasma propulsion system. Both NASA GRC (non-Li) and JPL (Li) are conducting development efforts on MPD thrusters.

Lithium Lorentz Force Accelerators

High power, lithium-fuelled Lorentz Force Accelerators (LFA's) or MPD thrusters are under development at JPL for ambitious future MW-class missions. Lorentz force accelerators are the only type of electric thruster with a demonstrated capability to process steady state power levels up to several MWe in a relatively compact device. In these engines a very high current is driven between coaxial electrodes through an alkali metal vapor or gaseous propellant. The current interacts with a self-induced or externally-generated magnetic field to produce an electromagnetic body force on the gas. Lithium propellant yields very high engine efficiency because it has low frozen flow losses. Because it has a very low first ionization potential and a high second ionization potential, very little power is expended in creating the plasma. Lithium LFA's can operate efficiently at power levels from 150 kWe up to tens of MWe and are therefore ideally suited for a variety of future missions requiring high power levels.

A steady state, radiation-cooled, applied-field thruster developed by the Moscow Aviation Institute (MAI) under JPL sponsorship has been operated at up to 188 kWe and has demonstrated 49 percent efficiency at an Isp of 4500~sec. The primary life-limiting component appears to be the cathode, which must operate at very high temperatures to emit high current levels thermionically. Tests at MAI demonstrated that the addition of barium vapor to the lithium propellant can significantly extend cathode life by reducing cathode temperatures. Recent work at JPL has focused on designing and fabricating a 500 kWe-class steady-state, radiation-cooled self field thruster and developing the capability to test lithium-fed engines at high power. Calibration tests of a lithium feed system developed by Princeton University and JPL demonstrated controllable flows over a range of 10 to 110 mg/sec with an uncertainty of 0.22 percent. This feed system will be used to obtain performance measurements at Princeton on a 30 kWe-class thruster built by MAI. Additional work at Princeton includes the development of an MHD code to model MPD thruster discharges using a novel solution technique and the investigation of anode phenomena in lithium-fed thrusters.

Non-Lithium MPDs

NASA GRC’s efforts are focused on non-Li propellants. Numerical codes developed at GRC have been used to design self-field MPD thrusters that can operate with inert gas propellants at predicted efficiencies in excess of 35 percent. It is anticipated that higher thruster efficiencies will be obtained with the addition of applied magnetic fields, leading to the development of MPD thrusters capable of achieving over 50 percent efficiency with inert propellants. Such designs would mitigate the safety and spacecraft contamination issues associated with condensable propellants such as lithium. In addition, recent numerical models developed by the Ohio State University (OSU) indicate that applied-field MPD thrusters may be able to operate at even higher efficiencies with any propellant by using the applied magnetic field as a true magnetic nozzle downstream of the plasma discharge. These combined results lend confidence that a robust, efficient MPD thruster can be built, and the primary goal of the high power MPD program is to demonstrate efficient, long-life thruster performance at the specific impulse values and power levels required by NASA mission applications.

The effort has several goals over the next 6 years, through a cooperative agreement with the Ohio Aerospace Institute. The first is to establish an MPD thruster modeling effort to simulate applied-field MPD thrusters using a modified version of the MACH2 MHD code. With help of the design codes, pulsed self-field and pulsed applied-field MPD thrusters from 100-kW to 10-MW are being designed, with the goal of achieving over 50 percent thruster efficiencies. Initial code verification will be on inert gas operation with later extension to advanced storable propellants (non-Li). Based on the Ohio State University MPD models, design and testing will be performed of a quasi-steady MPD thruster in which the primary applied magnetic field is positioned downstream of the electrodes. The performance of this design will be evaluated using inert gas propellants over a range of discharge currents and magnetic field strengths. The experimental results will be compared with the OSU simulations to validate the MPD magnetic nozzle concept.

The next phase will develop a water-cooled, steady-state MPD thruster operating in both self-field and applied-field mode. The steady-state thruster will be operated over a power range of 100 to 500 kW, with the goal of demonstrating thruster efficiencies of at least 50 percent with an inert gas propellant. Component wear will be measured, and techniques to mitigate electrode erosion will be evaluated. The current goals will lead to the design and development of efficient, MW-class MPD thrusters with limited ground testing at 100-kW-class, steady-state power levels. If the technology development is successful, an augmented program will provide for the development of steady-state MW-class thrusters and long duration ground testing in a simulated space environment.

Specific program goals to be achieved using augmented funding include several parts. Development of electrode voltage and thermal distribution models is needed to fully understand the performance of an MPD thruster. Electrode sheath models used to predict total voltage and electrode thermal models used to predict component wear would be developed and integrated into the numerical simulations. Current models are either empirical fits to existing geometries or heuristic approximations to the actual physical processes, and need to be upgraded to rigorous physics-based models to further our understanding of the complex principles underlying MPD thruster operation. Steady-state thruster performance at power levels up to 1-MW will be measured, and new designs will be evaluated with the goal of achieving over 50 percent efficiency in a steady-state, MW-class device. Finally, a long-duration (minimum 500 hr), MW-class MPD thruster endurance test will be conducted to validate thruster designs and to establish the feasibility of long term thruster operation in a space environment.

VASIMR

NASA under the leadership of Dr. Chang-Diaz at JSC is also developing the advanced VASIMR concept. The VASIMR system is a high power, electrothermal plasma rocket that is capable of exhaust modulation at constant power. It consists of three major magnetic cells: “forward,” “central,” and “aft,” where plasma is respectively injected, heated and expanded in a magnetic nozzle. This magnetic configuration is called an asymmetric mirror. The forward end-cell handles the main injection of propellant gas and the ionization subsystem; the central-cell acts as an amplifier to further heat the plasma to the desired magnetic nozzle input conditions. The aft end-cell is a hybrid two-stage magnetic nozzle that converts the thermal energy of the fluid into directed flow, while protecting the nozzle walls and insuring efficient plasma detachment from the magnetic field.

During VASIMR operation, neutral gas (typically hydrogen) is injected at the forward end-cell and ionized. The resulting plasma is heated with RF energy in the central cell to the desired temperature and density, by the process of ion cyclotron resonance. After heating, the plasma is magnetically (and gas-dynamically) exhausted at the aft end cell to provide modulated thrust. The VASIMR concept is envisioned as eventually evolving to power levels up to 100 MW. Current efforts are focusing on a flight opportunity on a Radiation and Technology Demonstration (RTD) mission with JSC, GSFC, and GRC teamed. The mission is in the study phase. The mission would demonstrate both 10 kW VASIMR and 10kW Hall thrusters.

HALL THRUSTER

NASA’s efforts in Hall thrusters consist of three parts, high-power engine development for primary propulsion, ground/space operation effects, and research in new thruster concepts including multimode operation.

High Power Engine Development

Over the past several years NASA has been investing in the development of high-power Hall engines for primary propulsion. The first phase of this effort focused on 10 kW engine technology. That effort culminated in FY00 with the 1000 hr demonstration by NASA GRC of the T-220 10 kW engine developed by Pratt & Whitney (formerly Space Power Inc.) under contract to TRW.

This is the longest operation ever achieved on a high power Hall thruster (>5 kW). This test indicates the availability of 10 kW Hall thruster technology for future NASA, commercial, and military missions. The thruster provided over 500 mN thrust at 2450 sec specific impulse (Isp) and 59 percent total efficiency with 10 kW input power.

The primary objectives of the life test were to determine the rate of erosion that occurs on the ceramic discharge chamber in order to refine future designs, and to demonstrate the overall durability of high power Hall thrusters. Thruster operation, including discharge current oscillations and propellant utilization, improved over the duration of the life test, especially after the first 500 hr. Quantitative measurements of material erosion were made throughout the test using a novel laser profiling technique. Preliminary review of the erosion data is encouraging. Performance measurements including thrust, Isp, and efficiency made at the beginning of the test and at 500 hr showed <2 percent variation.

High power Hall effect thrusters offer many advantages for Earth orbital and space transfer vehicles including an attractive combination of high specific impulse (as compared to chemical thrusters) and high thrust-to-power ratio (as compared to ion thrusters). The net result is a fuel efficient transfer with a reasonable trip time. The primary objective of the High Power Hall Thruster effort is to develop and demonstrate Hall thruster systems for primary propulsion. Early emphasis will identify the key development paths for increased performance, reduced mass, and longer life. Long term goals include the demonstration of a 50 kW thruster engineering models for transition to flight system development over the next 6 years.

FY01 activities will address the need for a 50 kW test-bed thruster. A procurement will be initiated for a design package of a test-bed thruster. Also in FY01 a thrust stand capable of carrying the weight and discharge current anticipated will be developed. In FY02 the test-bed thruster will be built and tested for baseline performance. In parallel with the building and testing of the baseline configuration a separate procurement for innovative component enhancements is planned. The out year efforts (FY03 to FY04) will consist of a second procurement for innovative components and the testing the component enhancements. Assuming sufficient funding a conceptual design review will be held at the end of FY04.

Multi-Mode Hall Thruster Research

Historically, development of Hall thrusters has been done in an evolutionary way where a known design was evolved into a family of thrusters of varying size and power. Presently, state-of-art thrusters operate at power levels between 0.75 to 4.5 kW, discharge voltages are nominally 300 V, and discharge chamber geometries are circular. In this task fundamental Hall thruster processes will be investigated in order to push Hall thruster technology to meet the requirements for future generations of Hall thrusters. These investigations will consider, but are not limited to, reduced beam divergence, increased range of efficient throttleability and increased thrust density at high power.

In FY00, The NASA D-80 multimode Hall thruster was evaluated at GRC. The thruster was developed by Rocketdyne and TsNIIMASH under contract to GRC and is the first attempt at a variable specific impulse Hall thruster for use in orbit insertion, maintenance and possible planetary applications. It was operated over a power range of 1 to 8 kW and in both single and two stage modes. Performance ranged from 1500 sec to over 3300 sec at >50 percent efficiency. It confirmed the possibility of high-efficiency, deeply-throttleable Hall thruster.

The FY01 effort consists of two parts based on the FY00 program. These two parts will be linked with the objective of understanding how to manipulate the ionization and acceleration processes within Hall thrusters by modifying the electron temperature and electric field distribution. This information is intended to be used to design the next generation of thrusters to operate more efficiently over a greater operating range.

The first effort is a derivative of FY00 activities. In this effort discharge chamber materials and geometry will be in investigated and optimized in regimes previously of limited interest. Next generation thrusters operating at voltages other than the SOA 300 V will require understanding the influence higher and lower voltages have on surface chemistry and modification to the electron energy distribution over the life of the thruster. Specifically, low power thrusters will be used for cost effective limited erosion and performance characterization. The type and configuration of ceramic material, along with the operating parameters, will be varied. A model will also be used to understand the influence these changes have on the distribution of losses within the thruster (i.e., ionization, radiation, etc.). Based on the results innovations such as composite discharge chambers and hybrid anode designs will be considered.

The second effort is a modification and evaluation of the FY00 funded 2-stage effort. In this effort a split anode TAL will be studied along with two hybrid concepts (The University of Michigan and Busek Co.) to understand the internal processes of the thruster. Understanding and manipulating the electric field within a thruster holds the promise of increase ionization and acceleration efficiency over a wide range of discharge voltage. In the out years concepts such as linear thrusters, racetrack designs, and thrusters with concentric channels will all be considered along with new concepts that come from the fundamental understanding gained the year before.

Ground/Space Correlations

The implementation of Hall thruster propulsion requires evaluation of the effect the plasma plume has on the spacecraft. This is traditionally accomplished by measuring ion current density and ion energy at various places within the plume during ground tests and calculating spacecraft integration effects based on these data. In this task the validity of this approach will be investigated by making specific ground test measurements with an SPT-100 that can be compared to in-orbit plasma measurements taken during operation of SPT-100 thrusters onboard two different EXPRESS Russian geosynchronous communication satellites.

In FY01 preparations for this comparison will be made. Data and sensors will be obtained from NPO-PM and a ground test conceptual design and detailed test plan will be written. In FY02 this effort will consist of multiple activities. The first activity will be the calibration of the sensors being flown on the Russian spacecraft. The response of a given probe to a known physical input will be determined for each of the five different types of Russian built sensors designed to measure ion current, ion energy (two different designs), pressure and electric field strength probe. At the same time equivalent probes will be fabricated for use in similar calibration tests and additional thruster tests. Following these efforts a series of thruster tests will be conducted designed to measure the plasma properties that are being measured in space using a combination of sensors and an SPT-100 Hall thruster. These data would then be compared to the in-space measurements. Based on availability of funding additional data may be taken at various background pressures and also various discharge currents, discharge voltages and potentially different thrusters. This will permit a more detailed evaluation, based on ground testing, of the effect of higher power and higher voltage Hall operations on plume/spacecraft interactions. In FY03 to 04 an analytic effort will be undertaken to quantify the difference between the ground and space data taking into account things such as charge exchange and chamber wall effects.

CONCLUDING REMARKS

During the last decade, NASA electric propulsion technology has been embraced by the user community. In-space propulsion continues to be a significant performance driver for future NASA mission applications. To meet known and anticipated mission performance goals in the future, innovative electric propulsion systems will be required. NASA has developed ambitious plans to advance electric propulsion technology to meet the needs projected at the end of the decade and beyond. Major emphasis will be on the future evolution of NSTAR ion technology and on the development of next generation ion systems for deep space exploration. A second focal point will be a renewed investment in 100 kW-MW class electric propulsion, seeking to develop technology to enable low-cost Earth space operations and to enable robotic and piloted space exploration endeavors. Investments in the area will include Hall thrusters, MPDs, PITs, and VASIMR. Academic involvement in the program will grow and a strong emphasis on technology transfer will continue. Efforts will be directed toward the development of commercial technology sources and the demonstration of program technologies to the level required by potential users. NASA technology activities are cross cutting and closely allied with other major national development efforts to ensure that a broad range of users are provided with new technologies in a timely and cost effective fashion. NASA will continue to identify and develop new electric propulsion technologies and invites the participation of innovative members of the community in the coming years.

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The last decade was a period of unprecedented acceptance of NASA developed electric propulsion by the user community. The benefits of high performance electric propulsion systems are now widely recognized, and new technologies have been accepted across the community. NASA clearly recognizes the need for new, high performance, electric propulsion technologies for future solar system missions and is sponsoring aggressive efforts in this area. These efforts are mainly conducted under the Office of Aerospace Technology. Plans over the next six years include the development of next generation ion thrusters for end of decade missions. Additional efforts are planned for the development of very high power thrusters, including magnetoplasmadynamic, pulsed inductive, and VASIMR, and clusters of Hall thrusters. In addition to the in-house technology efforts, NASA continues to work closely with both supplier and user communities to maximize the acceptance of new technology in a timely and cost-effective manner. This paper provides an overview of NASA's activities in the area of electric propulsion with an emphasis on future program directions.

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